International Journal of Scientific Research in Physics and Applied Sciences
Research Paper

Vol.8, Issue.4, pp.22-26, August (2020)
E-ISSN: 2348-3423

Photon Emission as a Promising Probe for Quark-Gluon Plasma in Heavy-Ion Collision

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Received: 07/May/2020, Accepted: 05/Jun/2020, Online: 31/Aug/2020

Abstract— The photon production from quark-gluon plasma in heavy ion collision is studied using a suitably modified dynamical quark mass depending on non-zero value of quark chemical potential and temperature. The total photon rate is computed for annihilation process ($q\bar{q} \rightarrow \gamma g$) and QCD Compton scattering process ($qg \rightarrow q\gamma$) or ($\bar{q}g \rightarrow \bar{q}\gamma$) incorporating parameterization factor in both the quark mass and coupling value. Photon spectra are calculated by integrating the production rate over the space-time history of the plasma. It is found that the emission rate to lowest order increases strongly with increasing the quark chemical potential.

Keywords— Photons; Quark-gluon Plasma; Heavy-ion collision.

I. INTRODUCTION

The colliders i.e. Relativistic Heavy Ion Collider (RHIC), Brookhaven National Laboratory (BNL) and Large Hadron Collider (LHC), European Council for Nuclear Research (CERN) are used to study the collision of heavy ion nuclei travelling at nearly relativistic speeds which enables physicists to unravel a new state of matter having very peculiar properties with initial non-vanishing net baryon density called the quark-gluon plasma (QGP) [1–3]. The most challenging objective of heavy ion collision is to establish the creation of quark-gluon plasma and study its properties at non-vanishing chemical potential. In order to confirm these conclusions and quantify the properties of the QGP, a comprehensive phenomenological study of heavy ion collision is inevitable [4]. Nevertheless, the heavy ion physics looks at different perspectives of measurements, thus it is pertinent to consider the chemical potential in an exotic state of matter that is formed in the central collision region of such high energies. Plenty of phenomenological models are available to study the properties of QGP, still a concrete evidence is awaited. Some important signatures used for the study of evolution of QGP and its detection are such as strangeness enhancement, elliptical flow, J/ψ suppression, electromagnetic probes such as photon and dilepton production. Among all, electromagnetic probes turn out to be very useful and promising phenomenological tool to study the heavy ion collision.

Photons and dileptons are useful probes to study the hot and dense matter (QGP) as they are created at the initial phase of the evolution of the QGP fireball and reach the detector without being affected by the final-state interactions [4–6]. These colorless particles are created via various processes during all stages of the collision. It is also considered that a signal of photons from the QGP phase is visible just above the critical temperature T_c . In contrast to hadronic observables which interact strongly and thermalize after the collision; and thus provide information in the late stages of the evolution in the heavy ion collision, electromagnetic probes have large mean free path and leave the medium without further interaction and therefore carry direct information on the time evolution of the system. Although these electromagnetic probes are important and useful in establishing the existence of QGP, still these probes suffer from some difficulties due to huge pollution from various sources. Overall these probes are of our particular interest for the study of QGP.

The various sources of photons in heavy-ion collision can be broadly classified into two categories-photons having thermal origins and the other group of photons emanating from cold processes. The cold process photons are considered to be as background and are not so important for the search of quark-gluon plasma. We cannot afford to ignore the background as these are not avoidable by the experiments. Further, depending on their origin the photons are categorised as prompt photons, thermal photons and non-cocktail hadronic decay photons. Prompt photons are produced at the very early stage of the collision due to the partonic Compton scattering and annihilation of quark-antiquark. At high transverse momentum, the prompt photons are the dominant source of direct photons. The thermal photons are produced through interaction of the constituents of the thermalized medium.

The non-cocktail hadronic decay photons are produced through the interaction of hadrons due to the hadronization of strongly interacting matter [7].

Since these thermal photons are produced in the very early stage of the heavy-ion collision and leave the zone without attenuation, thus the contribution of the initial towards photon emission rate is large [8]. It is widely accepted that the initial phase of the evolution of quark gluon plasma is sensitive to the photon spectra in the low and intermediate transverse momentum k_T region. The experimental results on photon spectra in heavy-ion collision at RHIC [9–11] and LHC [12] show an excess of photons as compared to the photons from hadron decay and hard perturbative mechanisms. This understanding about the thermal photons getting radiated in the initial stage where the flow effects would be less is referred as direct photon puzzle. Although perturbative quantum chromo dynamics (pQCD) calculations qualitatively agree to the experimental results of RHIC and LHC [13], but a more convincing reconciliation is still awaited.

In the past, the photon production has been studied by ignoring the quark chemical potential [14–19]. Further Hammon, Geiger and their collaborators [20, 21] have calculated the photon production rate from QGP at finite chemical potential [22–26]. Also Biro, Strickland and group [27, 28] have computed the photon emission for the baryon free hot and dense matter which is in chemically equilibrium. The above understanding and calculation of photon production rate would get modified while considering it at finite chemical potential. Thus, we exclusively focus on photon emission for one loop level at finite chemical potential to discover the effect of chemical potential on photon yield. The calculations are performed for longitudinal expansion that is parametrically suited for RHIC energy. Also the results for longitudinal and transverse expansion are almost similar and surprisingly, photons production is much affected by longitudinal expansion at high temperature, so transverse expansion is not taken into account [29].

The paper is organized as follows. In section II we compute the photon emission rate from hot and dense matter i.e. QGP. In section III we report our results and in section IV we give conclusion.

II. PHOTON EMISSION RATE CALCULATION FROM HOT AND DENSE MATTER

In the QGP phase, the photon emission occurs mostly through quark-antiquark annihilation process. Photon yield is calculated by integrating the production rate over the space time volume of the collision. In this article, a simple phenomenological model is formulated for strongly interacting hot and dense matter i.e. QGP at finite temperature and baryon density incorporating the parametrized factor in the modified quark mass and coupling value. And further we use the thermal Hamiltonian process to get thermal dependent quark mass and it gets modified due to its dependency on temperature and chemical potential. The Hamiltonian for QGP is expressed as [30]:

$$H(k,T) = H_0(k,T) + \frac{1}{2k}\gamma_q g^2(k)T^2 \quad \ldots\ldots \ (1)$$

where first term, $H_0(k, T)$ is unperturbed Hamiltonian and second term is the effective mean field potential between the particles in which $g^2(k)=4\pi\alpha_s$ with QCD strong coupling constant αs defined as;

$$\alpha_s = \frac{4}{(33-2N_f)\ln(1+\frac{k^2}{\Lambda^2})} \quad \ldots\ldots. \ (2)$$

Using Hamiltonian equation (1), we define the quark mass. The expression of quark mass is obtained by replacing T^2 by $(T^2 + \mu^2/\pi^2)$ [5, 22–25]. Now the quark mass depends on temperature and it is also a function of chemical potential. Since infrared divergence occurred in the limit when quark mass approaches to zero, this kind of divergence can be removed in the presence of quark mass which include the higher order effects from the interaction of the quarks [14,15]. Thus a dynamical quark mass uses as a finite value which is suitably modified by Kumar et al. [31, 32]:

$$m_q^2(T,\mu_q) = \gamma_q \frac{16\pi}{(33-2N_f)} \frac{1}{\ln(1+\frac{k^2}{\Lambda^2})} (T^2 + \frac{\mu_q^2}{\pi^2}) \quad .. \ (3)$$

where k is known as low momentum cut off with quark flavour $N_f = 3$, Λ is QCD parameter and $\gamma_q = 1/6$ is the quark phenomenological parameter taken by Ref. [31,32]. These parameters are nicely fit into our calculation. Using strong coupling constant and modified quark mass, we study the photon emission at finite temperature and chemical potential for the quark flavour $N_f = 3$. It will be of considerable interest to extend our present work to account for these effects at the hot phase of temperature T = 0.35 GeV. At last, we compare the outputs with our earlier results at zero chemical potential and other theoretical works.

Photons as a promising observable of quark-gluon plasma has caught the imagination of the researchers in high energy physics. Many researchers have contributed immensely to establish the existence of quark- gluon plasma(QGP) in heavy-ion collision. All these previous works motivated us to concentrate on photon emission and contribute in this front. In this work, we compute the photon production rate at finite quark chemical potential considering the QCD quark-antiquark annihilation process and Compton process. The lowest order contributions to the photon production rate are the quark-antiquark annihilation process ($q\bar{q}$ → γg) and QCD Compton scattering (qg → qγ) or ($\bar{q}g \to \bar{q}\gamma$) which appear at one loop level for a given system of quarks and gluons. The calculation is performed at hot and dense phase of the plasma i.e. QGP temperature T = 0.35 GeV for three flavors i.e.$N_f = 3$ with the Juttner distribution functions [27,28,33] Inserting the distribution funtions one can obtain the expression for photon emission rate through annihilation process at finite quark chemical potential [28, 33–35]:

$$E\frac{dn^{Ann}}{d^3kd^4x} = \frac{2\alpha\alpha_s}{\pi^4}\lambda_q\lambda_{\bar{q}}T^2e^{-E/T}\sum_f e_f^2[\ln(\frac{4ET}{k_c^2}) - C_{Euler} - 1] \quad ...(4)$$

where $k_c = 2m^2$. In the summation, 'f' stands for quark flavor while e_f is the electric charge of the quark q in units of the charge of electron. Similarly, we perform another dominant one loop calculation of Compton process q($\bar{q}$)g → q($\bar{q}$)γ as [28, 33–35]:

$$E\frac{dn^{Comp}}{d^3kd^4x} = \frac{2\alpha\alpha_s}{\pi^4}\lambda_q\lambda_g T^2e^{-E/T}\sum_f e_f^2[\ln(\frac{4ET}{k_c^2}) - C_{Euler} + \frac{1}{2}] \cdots(5)$$

With C_{Euler} = 0.577216 and fugacity for quark and gluon are taken as 0.02 and 0.09 [25, 33]. The total photon spectrum is calculated by integrating the rate over the space time evolution of the fireball created in heavy- ion collision for both channels. It is expressed as [25, 34, 36]:

$$\frac{dn}{d^2k_T dy} = \int d^4x(E\frac{dn}{d^3kd^4x}) = Q\int_{\tau_1}^{\tau_2}\tau d\tau\int_{-y}^{+y}dy(E\frac{dn}{d^3kd^4x}) \cdots(6)$$

Where τ_1 and τ_2 are the initial and final time, y is the rapidity of nuclei and k_T is transverse momentum, we obtain photon spectra for annihilation and Compton channels.

III. RESULTS AND DISCUSSION

We discuss the two important production sources of the electromagnetic emission from QGP at finite chemical potential in relativistic heavy-ion collision. The photons are produced in the space-time evolution of the plasma due to the interaction among quarks and antiquarks or quarks (antiquarks) and gluons. The results may be of importance concerning photon production as a signature for the creation of a quark-gluon plasma. We show the extended calculations of photon radiation with the effect of finite quark chemical potential for quark flavor $N_f = 3$. A suitably modified non-zero dynamical quark mass dependent on temperature and chemical potential is considered for the computation of photon production rate. The results obtained here is encouraging and photon yield found to be enhanced as compared to zero quark mass case and for quark mass with zero chemical potential.

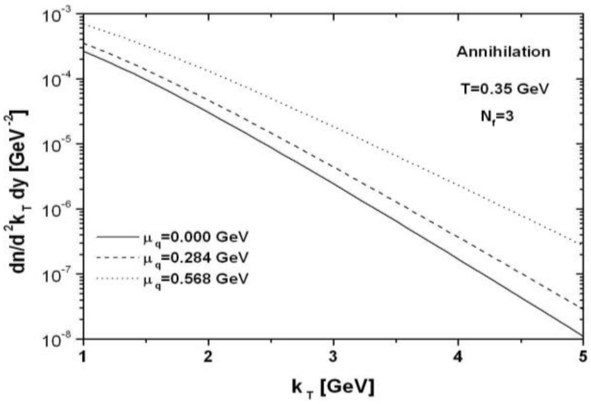

Fig. 1: Photon production rate through annihilation process.

Fig. 1 depicts the photon production rate at the hot plasma temperature T = 0.35 GeV through the annihilation process for quark flavor $N_f = 3$. It is found that the production rate is an increasing function of quark chemical potential μ_q . The temperature above the critical temperature (T > Tc) is used to compute the integral of the production rate of thermal photons as a signal of photons from the QGP phase is visible just above this critical temperature Tc . The modified quark mass at finite chemical potential generates a significant enhancement in the production rate and seems to be large at such hot phase of temperature.

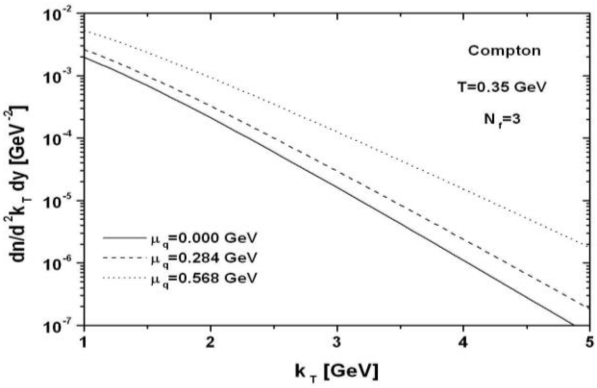

Fig. 2: Photon production rate through QCD Compton process.

Fig. 2 elucidates the photon spectra at temperature T = 0.35 GeV through the Compton channel. The photon yield is enhanced more and ahead in comparison to the annihilation process in the presence of finite chemical potential. In the Compton process, photon emission rate increases with the order of one as compared to annihilation process. Our model results are much enhanced from the earlier results without the chemical potential [32] and in good agreement with other work in the presence of quark chemical potential [25, 26, 28, 33–37].

IV. CONCLUSION

In this paper, a different formalism has been developed for the computation of photon production rate from QGP. We compute the photon production rate by considering the QCD quark-antiquark annihilation process and Compton process. The lowest order contributions to the photon production rate are the quark-antiquark annihilation process ($q\bar{q} \to \gamma g$) and QCD Compton scattering (qg → qγ) or ($\bar{q}g \to \bar{q}\gamma$) which appear at one loop level for a given system of quarks and gluons. The total photon yield is computed by integrating over the plasma volume created by the expansion and is compared with other theoretical works. Infrared divergence appears in the calculation as the quark mass approaches to zero, which ultimately yields a low theoretical production rate as compared to experimental result. Therefore, we consider a non-zero quark mass depending on chemical potential and temperature. Thus a suitably modified quark mass depending on temperature and chemical potential ie. dynamical quark mass bearing a finite value is used for the calculation of photon production. Overall the calculation of photon production rate as a function of transverse momentum incorporating the parametrization factor in the modified quark mass and coupling value gives much enhanced results from the earlier results without the chemical potential [32]. The presence of quark chemical potential enhances the photons production rate. Also the production rate of our model with the flavor $N_f = 3$ has an improvement over other reported results. Thus, the results obtained here are important for the understanding of the evolution of QGP and studying the properties of QGP.

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